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Interdisciplinary Industry-University Collaboration: Lessons from an Operations Improvement Project

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A six-month *Leaders for Manufacturing* student internship at ALCOA, Lafayette brought together faculty from the Schools of Engineering and Management at MIT, and identified a promising operations improvement opportunity in tube manufacturing. This experience led to collaboration between ALCOA and MIT to bridge gaps between engineering and planning, and integrate successive stages in the manufacturing process. Participants in the project included production management and planners, process engineers at the ALCOA Technical Center, and MIT undergraduate and graduate students in engineering and management. The project not only sensitized management to the importance of taking a systems view of process planning but also generated several tangible "products," including the development of performance metrics, diagnostic methods, and software for short-term and medium-term planning. The project also led to undergraduate and graduate thesis research at MIT and provided examples for classroom use. This paper presents a historical perspective of the collaboration process for this project, and discusses the enablers and challenges in conducting interdisciplinary, industry-university collaborative projects, including issues of goal congruence, mechanisms to foster collaboration, exploiting the synergies between education, research and practice, and the impact of organizational transitions.

1. Background

The *Leaders for Manufacturing* (LFM) program is a partnership for education and research in manufacturing and is composed of the Schools of Engineering and Management at MIT and thirteen U.S. firms. The program's vision is to discover and translate into teaching and practice principles that produce world-class manufacturing and manufacturing leaders. A centerpiece of the program is a dual degree (engineering and management) masters' program that includes a 6-month on-site internship project for each student at one of the partner companies, supervised jointly by engineering and management faculty. The LFM program also supports and facilitates interdisciplinary manufacturing research.

ALCOA, one of the partners in the LFM program, is the world's largest aluminum company, with manufacturing and sales operations at over 120 locations in 20 countries, and annual revenues exceeding $10 billion. The company's Extrusion/Tube System produces a wide range of aluminum extrusions and drawn tubes for the aerospace, commercial, building and construction, and automotive industries. The system's largest plant, located at Lafayette, Indiana, is over 50 years old, occupies 2 million square feet, and employs over 1000 people. The tube manufacturing process consists of ingot casting,

extrusion of ingots into intermediate-sized tubes or "**blooms**", and subsequent cycles of cold drawing and annealing, followed by finishing operations. Figure 1 shows a simple schematic of this process flow. The Lafayette Works is organized into three plants–*ingot plant, extrusion plant*, and *tube mill*–each with its own manager reporting to the Location Manager.

The operations of the tube mill resemble a large job shop. Blooms received from the extrusion plant first undergo a pointing operation (to crimp one end prior to drawing operations), and are subsequently processed at draw benches (that pull each tube through a die to reduce its cross-sectional area), annealing ovens (to relieve stress and meet material properties), and finishing operations (e.g., straightening, cutting) in a myriad of sequences (Balakrishnan and Brown [1992] describe these processing steps in greater detail). Overhead cranes transport batches of tubes in racks between workstations and intermediate storage areas. Tubes are largely produced to order; each batch, containing tens or hundreds of tubes, corresponds to a single product ordered by a specific customer. The tube mill produces more than 5000 drawn tube products in different alloys and sizes. Each product has a unique sequence of operations, depending on the deformation and thermal operations needed to convert the available bloom to the desired finished size and specification. In 1988, the Extrusion/Tube Division embarked on a Tube Mill Rationalization program to reduce cycle time and improve yield. The program sought to streamline the operations of the tube mill by classifying the large number of tubular products into a few groups based on similarity in processing paths, and assigning dedicated facilities (i.e., pointers, draw-benches, and finishing equipment) to each group.

Senior managers associated with the Tube Mill Rationalization program invited an LFM intern to join the team. The LFM internship experience has many objectives: to provide an opportunity for students to observe practice, apply and teach principles they have learned, to provide value to the partner companies by addressing real manufacturing problems combining both engineering and management issues, and to motivate interdisciplinary LFM theses. ALCOA's proposal to structure a student project around tube mill rationalization was appropriate because it met the LFM internship's multiple objectives. Since the project required knowledge of metal-forming operations as well as group technology methods, it brought together faculty with research interests in deformation processes and operations planning as the engineering and management advisors. This interaction led to a subsequent broader collaboration that extended beyond the initial thesis. The LFM student who chose this project, Timothy Loucks, began his internship in the tube mill at Lafayette in June

1989. The initial phase of the project focussed on understanding the manufacturing processes and current operations at the plant. Several visits to the plant and regular communications with the student enabled the faculty advisors to become acquainted with the Lafayette Works' operations and organization. Loucks became a member of the rationalization team, participating in the team's regular meetings and providing some analytical assistance. The tube mill plant manager served as his on-site company advisor.

During a mid-stream review of the internship, the supervisors realized that the rationalization project was making certain implicit assumptions that merited reexamination. Since the project concentrated on tube mill operations, its scope was limited to local rather than plant-wide improvements by assuming that the tube mill was decoupled from the rest of the plant. In particular, the project assumed that the current bloom sizes produced by the extrusion plant could not be changed, and so it did not consider alternative processing paths for each product. The faculty supervisors felt that reviewing these basic project assumptions and examining the entire process flow could produce significant payoffs. For instance, changing the set of standard bloom sizes or relaxing certain processing constraints (based on better process understanding) could potentially have greater impact on tube mill productivity compared to grouping the products solely based on their current processing paths. Loucks' internship, therefore, became a test-of-concept project to illustrate the advantage of taking a broader view of the rationalization project to span both extrusion and tube mill operations (Loucks [1990]). Working with the process planners, Loucks developed a classification of the fundamental manufacturing constraints on the tube drawing process, and used a graphical representation of these constraints to illustrate the tremendous flexibility inherent in tube manufacturing.

2. Objectives and scope of the collaborative research project

Loucks' internship identified two research opportunities of interest to the faculty supervisors and valuable to ALCOA: (i) develop engineering *process* models for extrusion and tube drawing that can enable ALCOA to critically examine current practice and exploit opportunities to improve productivity; and (ii) develop an integrated *operations* model of extrusion and tube drawing, incorporating the flexibility and costs at both stages, to select bloom sizes and processing paths that optimize joint performance and determine sensitivity to various process constraints. These models and their underlying concepts might have broader applicability to ALCOA's other business units (e.g., rolling operations) as well. Consequently, the Lafayette operations presented an exciting opportunity for a mutually

beneficial industry-university, engineering-management collaboration consistent with the LFM program's vision.

Since the ALCOA Technical Center (ATC) has expertise in both process modeling and manufacturing simulation, the two faculty members jointly proposed a multi-year collaborative effort involving the ATC, the Lafayette plant, and MIT. The project would be supported by the LFM program, but also requested nominal funding from the Extrusion/Tube System to ensure the operating division's commitment to the project. The plant participants would educate the team about plant operations and collect the necessary data for diagnosis and analysis. The ATC would not only provide process insights but, more importantly, internalize the project methodology and serve as the agent for wider dissemination of this methodology to other facilities in the Extrusion/Tube System, and possibly other divisions as well. The project would support MIT graduate students to assist in developing and testing new models.

The broad mission of the project was to highlight the strategic importance of medium-term process planning decisions for metal forming operations, argue for tighter integration of the two intermediate stages–extrusion and tube drawing–in the tube manufacturing supply chain, and emphasize the close interplay between process engineering and planning activities. Process planning refers to decisions regarding the processing steps necessary to transform raw materials to finished products. It has two distinct components–a short-term or operational activity to select the specific processing steps and create the lot ticket for each incoming order, and a medium-term component to decide, for instance, the standard ingot sizes and bloom sizes that the ingot and extrusion plants must produce. These latter decisions are medium-term because they require investments in tooling (e.g., extrusion dies and mandrels) and entail process experimentation to produce good quality product; they also constrain the choice of processing paths in the short-term. Like other plants in the metal forming industry, the Lafayette Works placed greater emphasis on day-to-day operational planning, assigning this task to two planners who reported to their respective supervisors in the extrusion plant and tube mill. For each incoming order, the tube mill planner first decided the processing steps within the tube mill, and then the extrusion planner prepared the lot ticket for the necessary bloom. The planners had to operate within predefined constraints (e.g., they had to work with existing bloom sizes), and the choice of processing paths was strongly influenced by past practices. The plant did not appear to have a deliberate, periodic process to address medium-term ingot and bloom sizing

decisions; rather, new sizes were sporadically introduced in response to specific high-volume orders.

The project proposal was based on the following set of hypotheses:

- Medium-term process planning decisions provide much greater leverage for improving performance (in cost, lead time, materials handling, quality) compared to merely fine-tuning the operational planning activity. Since the project was concerned mainly with the extrusion-tube mill interaction, it focussed on bloom sizing decisions (i.e., selecting standard bloom sizes) and did not explicitly consider ingot sizing.
- The choice of bloom sizes affects the relative workload of the extrusion plant and the tube mill. Therefore, bloom sizing decisions must simultaneously consider manufacturing issues (cost, productivity, capacity, yield) in both plants; they must be made jointly by both plant managers.
- Unlike the operational planning activity that considers each incoming order one by one, bloom sizing decisions must consider all products simultaneously and must be based on demand forecasts of the product mix.
- Bloom sizing decisions must incorporate process constraints. Better process understanding can potentially lead to relaxing the most restrictive among these constraints, and therefore improve the bloom choices.

Specific goals of the project were to: (i) validate these hypotheses, and (ii) develop decision support tools for medium-term process planning, e.g., a model to select a "good" set of standard bloom sizes. The validation exercise had three main purposes: (i) to ensure that the proposed decision support tools would indeed be useful to the plant, (ii) to convince management of the benefits of a systematic medium-term review process, and (iii) to illustrate how to perform diagnostic analysis. A by-product would be the identification of information deficiencies. The planning tools developed during the project would be generic; the Lafayette Works would serve as the pilot plant to test and implement these methods.

MIT faculty hoped to benefit from this project in two ways: (i) the project would motivate specialized research in process modeling and operations research. The opportunity to use real data from the manufacturing facility would enrich this research; and (ii) the project presented a genuine opportunity for the engineering and management faculty to collaborate on a framework to integrate process engineering and planning since these activities are closely interrelated. Process constraints, developed using engineering analysis, serve as input parameters for planning models; in turn, the planning models can

prioritize and focus process engineering efforts by evaluating the economic impact of extending process capability. By setting an example of engineering-management collaboration for the project, the faculty hoped to stimulate similar cooperation at the plant and the Technical Center.

3. Project execution

The project proposal received strong support from an ATC Division manager (who was also ALCOA's liaison to the LFM program) at the corporate level, and the tube mill manager at Lafayette. After discussions and presentations at the plant and the ATC, the Extrusion/Tube System approved this proposal (in 1991). Funding for the project would be appropriated annually, based upon the project's progress and the plant's evolving needs and priorities. The faculty had requested that the plant assign a specific person at the supervisory level, at least part time, to participate in the project by providing data on plant operations, performing some of the analysis, and critiquing any models and methods developed by the researchers. Initially, the two ALCOA project champions–the ATC division manager and the tube mill plant manager–decided that they would themselves serve as liaisons for the project; these managers and the faculty members formed the "core project team"[1]. The plant and ATC agreed to identify other appropriate team members as needed. Over the next two years, the project progressed through 3 broad phases: (1) understanding and diagnosis of tube mill operations, (2) analysis of the extrusion-tube drawing linkage, and (3) modeling, validation, and recommendations. We briefly discuss each of these three phases in turn, emphasizing the project environment, collaboration process, and tasks and outcomes in each phase.

3.1 Phase 1: Understanding and diagnosing tube mill operations

Since the faculty were already acquainted with the tube mill, the team decided to first collect data and analyze tube mill operations to verify the initial hypothesis regarding the importance of bloom sizing decisions. After this validation phase, the team hoped that the extrusion plant would participate in the project, presenting the constraints and productivity issues they face in supplying different bloom sizes. The need to simultaneously consider both extrusion and tube drawing operations for medium-term process planning would then become apparent, paving the way for the proposed integrated process and planning models. The MIT team set out to first understand the plant's "standard practice" rules for producing drawn tubes.

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[1] We will henceforth refer to the core ALCOA-MIT team as the "team"; the two faculty members and their students constitute the "MIT team".

Current planning procedures:

Standard practice refers to a set of rules, reflecting constraints imposed by the drawing and heat treatment processes and material limitations, that the planner must follow in deciding the processing steps for each drawn-tube. For instance, the rules specify the maximum achieveable reduction in cross-sectional area (CSA) per draw, the maximum permissible CSA reduction between annealing operations, the amount of cold work needed to meet material properties, and so on. These rules are based on the plant's tube drawing experience over several decades and are intended to ensure consistent product quality and adequate yield. To change a rule or use a processing path that might violate one or more rules, the process planner must get the approval of metallurgists and process engineers.

Let us first describe the plant's current (operational) process planning procedures. When placing an order for a drawn-tube product, the customer specifies the alloy, outer diameter (OD), wall thickness (WT), length, temper and other material properties of the tubular product, as well as the desired number of tubes and a due date. The primary dimensions of interest for process planning are OD and WT. The processing path from ingot to finished product is decided in two stages. First, the tube mill's process planner: (i) selects an appropriate standard bloom size, (ii) determines the necessary drawing and heat treatment operations to convert the chosen bloom to the finished product, and (iii) orders the required bloom from the extrusion plant. Upon receiving the bloom order, the extrusion planner specifies the extrusion process parameters (equipment, tooling, extrusion speed, allowances, etc.), and orders the required number of billets[2] from the ingot plant.

The tube mill planner uses a *Tube Area Chart* (Figure 2), a two-dimensional chart with OD and WT defining the two axes, to decide the processing steps in the tube mill. Each bloom or tube corresponds to a single point on this chart. Every pass on the draw-bench reduces the OD and WT (and hence the CSA) of the incoming workpiece, and therefore corresponds to moving from the point representing the starting workpiece to another point closer to the origin. If the CSA difference between the bloom and the finished tube is large, multiple drawing passes might be necessary to convert the bloom since process constraints impose an upper limit (which we call the maximum CSA per draw) on the amount of CSA reduction in each pass. As shown in Figure 2, the overall tube process

[2]The ingot plant casts solid cylindrical ingots in a few standard diameters, and maintains these ingots in inventory. Billets are ingots cut to the required length for each order.

plan for a product corresponds to a series of "south-westerly" moves from the point representing the chosen bloom to the finished dimensions.

To decide the process options for an order, the tube process planner uses the following manual procedure, called "pinning". First, he selects one of the currently available standard bloom sizes, and marks the starting (bloom) and ending (finished tube) points of the process plan with pins on a Tube Area Chart. He then partitions the connecting line into one or more segments, each corresponding to one drawing pass. The CSA reduction in each segment must not exceed the maximum CSA reduction per draw. Pins at segment ends, adjusted to coincide with the closest available die sizes, represent the tentative intermediate tube sizes. The planner then introduces intermediate annealing steps as needed (if the total CSA reduction exceeds a threshold specified by the standard practice rules). Pinning is necessary only for orders involving new sizes or specifications. For tubular products that the plant has previously produced, the tube planner retrieves and uses the most recent process plan (unless the required bloom size is not currently available).

The tube planner had previous shop floor experience as a draw-bench operator and production team leader, and relied heavily on this experience to choose process plans that operators can follow easily to produce tubes with consistent quality and acceptable yield. The set of "standard" bloom sizes has gradually evolved over time in response to changing demand patterns. The extrusion plant is cautious about introducing new bloom sizes (due to concerns that it might affect extrusion productivity, particularly since smaller blooms are harder and more time-consuming to produce). If a particular finished size has high demand and the current bloom for this product has a significantly larger cross-sectional area (necessitating many drawing and annealing steps), then the tube mill might request the extrusion plant to consider producing a smaller and thinner bloom size. Adding a new bloom size entails discussions and approvals at higher management levels.

This first step to understand current planning practices provided several important lessons:

(i) The tube planner (and shop-floor workers) can provide valuable process insights, and should participate as a member of the team.

(ii) "Manufacturing effort" in the tube mill roughly correlates with the number of drawing passes and annealing operations, which in turn depends on the CSA difference between the bloom and the finished tube.

(iii) The tube planner could benefit from a computerized planning tool with a graphics interface that displays the limits imposed by standard practice rules, available bloom sizes, and chosen process plan on a Tube Area Chart.

(iv) Although ALCOA is a pioneer in aluminum extrusion and tube drawing, the company's process modeling efforts had focussed on other processes such as rolling (which accounts for a larger share of the company's revenues and profits) rather than tube drawing. The standard practice rules appeared to be largely experience-based.

(v) Instead of the current mode of sequential planning by two planners reporting to two different supervisors, extrusion and tube planning (and possibly even ingot planning) activities should be more closely coupled to simultaneously account for prevailing workloads, yield rates, and costs in both plants. Such an integration would also reduce the planning lead time.

(vi) The plant did not regularly review the overall product mix, bloom sizing decisions, and planning rules.

Diagnostic analysis of tube mill data:

Studying the standard practice rules and understanding the planning process raised several initial questions. Is there any regular pattern in the distribution of tube sizes that customers order most frequently? What is the range of products covered by each bloom? Does actual practice follow the standard practice rules? Is it possible to reduce tube mill effort even with the currently available set of blooms? To answer these questions, the team decided to collect production data for a specific product group, i.e., a range of OD and WT values for a specific alloy, that covered a large number of tubular products and accounted for about 20% of the tube mill's production. The plant provided data on the processing history for every batch of tubes in this product group manufactured during the preceding three-month period. Since production control was not computerized (except to print out lot tickets, which were not stored for later use), the necessary data had to be manually transcribed from over 1000 actual lot tickets, and then entered into a spreadsheet which we will refer to as the "tube mill database". This database contains information for over 300 products; these products use 37 different bloom sizes, and account for over a million pounds (and over 3 million feet) of drawn tube production.. Data analysis was the responsibility of the MIT team.

The exploratory data analysis had four objectives:

(i) understand the demand distribution, i.e., identify high and low volume products, and visually assess the relative location of products on the Tube Area Chart to identify clusters;

(ii) map the products and blooms on the Tube Area Chart to discern the rationale for choosing standard bloom sizes, and validate the principle of choosing the closest available bloom for each product;

(iii) characterize the distribution of parameters such as CSA reduction per draw used in the actual process plans, and compare these with standard practice; and,

(iv) summarize the distribution of bloom usage.

Since this analysis required extensive plotting and charting capabilities, the MIT team decided to develop PC-based graphics software that can display products and blooms on a Tube Area Chart. An undergraduate student subsequently developed a more comprehensive tool called the "Tube Area Chart Viewer" (TACV) that includes capabilities to display the constraints implied by standard practice rules, and perform operational planning.

To assist in this exploratory data analysis, two MIT students–a doctoral student from the Operations Research Center, and an undergraduate student from the Electrical Engineering and Computer Science department–joined the MIT team. The *Operations Research Center* (ORC) is an interdepartmental graduate program with affiliated faculty and students from several departments in the Schools of engineering and science, and the Sloan School of Management. ORC students receive rigorous training in the theory and methods of OR, and many of them participate in LFM-sponsored research projects as a way to get exposure to practical manufacturing problems that can motivate thesis topics. Another program at MIT, the *Undergraduate Research Opportunities Program* (UROP), encourages undergraduate students to participate in research teams by providing financial incentives or course credit. The UROP program is voluntary; it attracts motivated students who want to learn about the research process and get experience applying their skills to practice.

The data analysis exercise provided the following insights, confirming conventional (management science) wisdom that a major benefit of any modeling exercise is not necessarily the end result but the discipline it imposes in collecting real data to validate assumptions and build the model.

- The demand distribution followed the familiar 80-20 rule holds: 16% of the products accounted for over 70% of the total production volume, and 7 out of the 37 bloom sizes accounted for over 80% of the total weight of blooms used during the quarter.

- The points representing finished products on the Tube Area Chart were not evenly distributed; however, it was hard to visually separate dominant product clusters that might each use a common bloom size. This observation indicated that more formal models and methods would be necessary to group products and select bloom sizes.
- The points representing current standard bloom sizes on the Tube Area Chart did not appear to be uniformly distributed either; furthermore, the distribution of bloom sizes did not seem to correlate with the product demand distribution. Closer examination of the finished sizes produced from each bloom revealed that the tube planner did not always choose the closest available bloom for each product. Since the number of draws increases as the CSA difference between bloom and finished tube increases, choosing the closest available bloom for each product minimizes the tube mill's effort. The fact that the planner did not always follow this principle indicated one of two possiblities: (i) minimizing tube mill effort is not the planner's sole criterion for choosing the starting bloom, or (ii) the manual planning procedure makes it difficult to quickly identify the closest available bloom, and so improving this procedure can reduce tube mill workload even with the current bloom set.
- Finally, for many products, the actual practice appeared to be much more conservative than the standard practice rules. For instance, the average CSA reduction per draw in the actual process plans was only 80% of the maximum CSA reduction per draw specified by the standard practice rules. Potentially, the number of draws could be reduced if the planner followed the standard practice limits more closely. The analysis also identified products for which the actual practice violated standard practice rules.

Besides illustrating the diagnosis process and drawing inferences from actual data, one of the team's important contributions during Phase 1 was to help define measures for the tube drawing workload imposed by each product. The tube mill did not have any well-established metric for throughput, effort or productivity (e.g., to measure production volume, some management reports used total weight while others expressed volume in terms of total length of tubes produced). Discussions of the data analysis results at the plant led to the definition of a new statistic called *drawn-feet* to measure tube drawing effort. The drawn-feet of each production lot equals the length of each tube multiplied by the number of draws and the number of tubes in that lot. Since the speed of the draw-bench is relatively constant and the equipment setup time for each lot is small relative to the actual drawing time, the drawn-feet metric correlates well with the total drawbench time (man hours) needed to produce that lot. This type of metric emphasizes to managers that reducing the number of draws reduces tube mill effort. Reducing draws has other benefits

such as decreasing material handling activity and improving yield. The team also developed a surrogate metric for annealing effort called *total rack area* (an estimate of the total CSA of all tubes entering the annealing oven, which approximates the number of annealing loads). By choosing good non-financial performance metrics such as drawn-feet and total rack area, the project could avoid controversies associated with using conventional cost accounting systems.

Using information from the tube mill database, the MIT team performed various types of what-if analyses aimed at verifying the potential to improve tube mill performance (i.e., reduce total effort). This effort initially focussed on possible improvements using only the current bloom sizes, and subsequently (in Phases 2 and 3) considered additional benefits obtainable by choosing optimal bloom sizes. The aim was to answer the following questions.

- What if the planner had followed the limits specified by standard practice rules instead of using the more conservative practices that we had observed from actual data?
- Which of the process restrictions are most limiting?
- What if these limits could be extended (relaxed) based on detailed process understanding and experimentation?
- What if the planner had chosen the closest bloom for each product?
- What if the plant replaced an existing bloom with a smaller size (in both OD and WT) that is closer to the products that use this bloom?

The results of this analysis clearly demonstrated that the tube mill could reduce total effort considerably even with the current set of standard bloom sizes and current standard practice limits. For instance, merely choosing the closest current bloom for each product would have reduced the total drawing effort by approximately 24%. Increasing the CSA reduction per draw (up to the standard practice limits) would have decreased the drawing effort by an additional 4%[3]. As an example, reducing the OD of one bloom by 23% and its WT by 10% decreased the drawing effort for its products by approximately 10%.

Phase 1 concluded with a presentation at the plant during which the MIT team summarized the results of the diagnostic analysis. Plant personnel were mostly accustomed to addressing problems with each order or product in isolation; the presentation provided them an opportunity to view the entire portfolio of products. For instance, they had not previously examined the distribution of demand, or viewed the relative location of products

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[3] For a given CSA difference between the starting bloom and finished product, increasing the value of CSA reduction per draw reduces the number of draws, thus decreasing tube drawing effort.

and blooms on the Tube Area Chart. The tube mill management was surprised by the magnitude of potential improvements. They acknowledged that a large portion of this improvement was easily achievable, but also questioned some of the assumptions and raised new issues. For instance, some products (particularly thin wall tubes) did not fully exploit standard practice limits because past experience had indicated that processing paths based on these limits can have very poor yield. This observation highlighted the need to better understand, through modeling or experimentation, the tube drawing process for thin wall tubes. Similarly, the planner did not always assign products to the closest available bloom because the old process plans (which are reused for repeat orders) are not systematically updated when a new bloom size is introduced.

An important concern about the suggested plan to reassign each product to its closest bloom was that this plan would require the extrusion plant to produce more of the small, thin wall blooms that require more time to extrude. Since the extrusion plant's performance is measured in terms of the total pounds extruded per month, they would prefer to produce larger, thicker blooms that have greater productivity (i.e., more pounds extruded per hour). This observation naturally led to the next phase of the project where the team began to address the tradeoffs between extrusion and tube drawing.

3.2 Phase 2: Extrusion-Tube integration

The discussions at the end of Phase 1 supported the project's initial hypothesis about the tradeoff between extrusion productivity and tube drawing effort, and the need to account for this interaction in medium-term process planning decisions (i.e., selecting standard bloom sizes). Quantifying this tradeoff first required understanding how extrusion effort and yield varies with bloom size. Again, instead of using monetary values to quantify extrusion effort, the team decided to focus on a non-financial indicator, namely, *effective extrusion speed* or "good" pounds per hour that the press can extrude for each bloom size. This metric accounts for both extrusion time and yield.

Parameter estimation and validation of assumptions:

Extrusion personnel assumed that the primary determinant of extrusion speed is the so-called *Extrusion ratio* which is the ratio of the CSA of the billet to the CSA of the extruded bloom. Extrusion speed decreases as extrusion ratio increases; thus, thin wall blooms, with small CSA and high extrusion ratios, have low speeds. The first step was to validate this claim by analyzing data on extrusion times for different bloom sizes. Another UROP student joined the MIT team to assist with this analysis. Because standards for extrusion

speed were not well-established, the relationship between actual extrusion speed and bloom dimensions had to be empirically estimated. Unfortunately, detailed lot-by-lot data was not available for extrusion operations and necessitated the use of aggregate figures for average extrusion time per lot, calculated from accounting data.

The data did not completely support the hypothesis that large, thick wall blooms necessarily have higher effective extrusion speeds. Instead, the plot of effective extrusion speed as a function of CSA had an inverted U-shape, i.e., the speed increases with CSA up to a certain level and then begins to decrease. This non-linear relationship is caused by two opposing effects. As CSA increases, the actual extrusion speed increases, but the total pounds scrapped also increases (hence the "good" pounds decreases) since the extrusion process entails some fixed scrap per batch (e.g., fixed lengths at the leading and trailing edges of each billet and bloom are discarded). Since extrusion ratio did not prove to be a good predictor of extrusion speed, the MIT team experimented with various other explanatory variables in order to express effective extrusion speed as a function of bloom dimensions. A simple, linear model with OD and WT as the independent variables provided the best fit ($R^2 = 0.86$).

The MIT team also analyzed the tube mill data to verify claims that thin wall tubes have low yield in the tube mill. Extensive analysis with numerous combinations of explanatory variables (OD, WT, OD/WT ratio, number of draws, lot sizes, and so on) did not reveal any discernible variation in yield with tube dimensions (the R^2 values were all less than 0.08). Managers at the facility had not previously performed such rigorous statistical analysis. This analysis, although not part of the original project charter, served to illustrate the importance of and ways to verify shop-floor intuition using operational data.

Extrusion-drawing tradeoff curves and sensitivity analyses:

The models for extrusion effort and tube drawing effort as functions of bloom dimensions and bloom-to-tube assignments, respectively, provided the foundation for analyzing the impact of bloom sizing and tube-to-bloom assignment decisions on both extrusion and tube drawing operations. The MIT team had first considered developing a model that minimizes the total cost of extrusion plus tube drawing, but decided instead to generate tradeoff curves between extrusion and tube drawing effort. This strategy offered two advantages: (i) it generates multiple scenarios (rather than a single "optimal" solution) that managers can use to assess the relative performance impact of process planning decisions on upstream and downstream operations. They can then choose the best

operating point on this curve for their facility based on economic and operational considerations; and, (ii) extrusion and tube effort can be measured in different units (e.g., press-hours and drawbench-hours, respectively) instead of converting both metrics to commensurate monetary units using controversial accounting data.

As in Phase 1, the tradeoff analysis first considered only current bloom sizes. The MIT team developed and solved a linear programming model that assigns each product to an available bloom in order to minimize total tube drawing effort for all products subject to an upper limit on the extrusion effort. By varying this upper limit, the linear program generates several points on the efficient frontier of the extrusion versus drawing effort tradeoff curve (Figure 3). This exercise demonstrated, for instance, that increasing the total extrusion effort from 20,000 to 25,000 extrusion-minutes (by selecting smaller bloom sizes) reduces the tube mill effort by approximately 50,000 drawing-minutes. However, subsequent increases in the extrusion limit produced only a much smaller payoff (e.g., with an additional 15,000 minutes in extrusion effort the incremental savings in tube drawing effort was only about 15,000 minutes). Using the optimization model, the MIT team also explored the sensitivity of the extrusion-tube drawing tradeoffs to variations in process parameters. This analysis revealed that the maximum CSA reduction per draw was the most influential parameter, i.e., modest increases in this limit produced considerable improvement in performance (e.g., increasing the CSA limit by 10% produced over 15% savings in tube drawing effort).

Concurrent with the data analyses and operations modeling effort at MIT, the Process Design and Reliability division at the ATC developed a preliminary finite-element model for the tube drawing process in order to illustrate to the plant personnel how this technique can help them better understand and improve the process. This second phase of the project ended with a joint presentation by MIT faculty and a member of the technical staff from the ATC to the managers, planners, and supervisors at the plant. The pictorial representation of the optimization results in the form of shifting tradeoff curves for different process parameter values (Figure 2) proved to be a powerful means to convince plant management about: (i) the potential for considerable savings in both extrusion and tube drawing effort relative to current practice, (ii) the need to judiciously select the operating point on the tradeoff curve due to the wide variation in the possible extrusion-tube effort values, and (iii) the need to better understand the tube drawing process and refine the standard practice limits, particularly the maximum CSA reduction per draw. The ensuing discussions on how the tradeoff curves might shift if new bloom sizes were introduced led to the project's

third phase, namely, to develop formal methods for selecting new bloom sizes. The discussions also motivated a second LFM internship project focussed on identifying and selecting optimal process parameters for the tube drawing process to improve yield (Dorah [1992]).

During the project's second phase, the plant went through some significant organizational changes. The tube mill plant manager, a member of the core team, became the project manager for a new plant and so had to reduce his involvement in the project. To provide the necessary plant-level information support, a planning supervisor in the tube mill was assigned the responsibility (in addition to his regular functions) of acting as the plant's liaison for the project. The new tube mill manager, transferred from another division, had prior experience in planning and logistics, and was emphathetic to the project. Other changes at Lafayette included a reorganization of the tube mill, and the appointment of a new supervisor for the main extrusion press that produced blooms for the tube mill. The plant also recruited an LFM graduate whose initial responsibilities included shop-floor supervision in the tube mill. The new tube mill management team provided a supportive environment to continue the project. However, the corporation's new Quantum Leap objectives (see, for instance, Kolesar [1993]) imposed pressures on the Extrusion/Tube System and the Lafayette Works to rapidly improve performance on many dimensions–cost, quality, delivery performance, and safety–prompting management to focus on immediate problems and reducing the plant's ability to participate actively in the project.

3.3 Phase 3: Modeling and recommendations

The project's final phase began to address the original objective, namely, to develop and apply a methodology for selecting an effective set of new bloom sizes taking into account both extrusion and tube drawing effort. Instead of treating the bloom sizing problem as a continuous optimization model over the infinite set of possible bloom OD-WT values, the team decided to consider only a discrete set of equally spaced values for OD and WT. The set of candidate bloom sizes was the set of feasible combinations (i.e., sizes producible by the extrusion press) of these OD and WT values. The MIT team developed and implemented five different heuristic methods to choose standard bloom sizes from the candidate set to minimize total tube drawing effort subject to a limit on the total extrusion time.

These methods were implemented in FORTRAN and C on workstations at MIT, and tested using data from the tube mill database. A "random" bloom selection method and the

current set of standard bloom sizes provided benchmarks for comparing the performance of the heuristics. The bloom sets chosen by the different methods varied in the number and types of blooms. For instance, one greedy method selected over 100 bloom sizes but achieved very low extrusion and tube drawing effort; at the other extreme, another method chose only 11 standard bloom sizes at the expense of higher effort for both stages. Comparing these results with current practice confirmed the considerable potential to improve performance in extrusion-tube operations through better bloom selection. For instance, the optimization exercise demonstrated that, using just 11 new bloom sizes (instead of the current 37 sizes), the Lafayette plant could achieve a 20% reduction in tube drawing effort compared to current practice. Permitting additional bloom sizes produced further improvement.

The MIT team presented the methodology and results (including specific bloom size recommendations) first to the senior management team at Lafayette (including the president of the Extrusion/Tube System and the Lafayette Location manager) and then to the tube mill supervisors and planners. When the discussion turned to implementing this methodology at Lafayette, the managers realized that the organization must first achieve closer integration of extrusion and tube drawing operations through organizational changes (in structure, systems, and incentives) before undertaking full implementation of the recommendations. So, they suggested a 3-stage implementation plan corresponding, respectively, to short, medium, and long-term actions. The new bloom size recommendations would be fully implemented only in the third stage. As we discuss next, the first two stages required additional modeling and analysis.

As the first step, the tube mill requested the MIT team to identify 5 or 10 important blooms from the current set of 37 blooms that they should immediately start monitoring closely (e.g., by ensuring adequate inventory levels of these blooms). Using a heuristic approach, the team chose the "top" 10 existing bloom sizes that together covered 80% of the mill's finished products.

For the second stage, the tube mill preferred the following "decoupled" strategy. They would first ascertain from the extrusion plant what range of bloom OD and WT extrusion was willing to produce, and then wished to select a small set of new bloom sizes in the specified range in order to optimize tube mill effort. Thus, the tube mill's medium-term implementation strategy required a redefinition of the optimization model. Instead of explicitly incorporating extrusion effort and jointly optimizing extrusion and tube mill

performance, the new "localized" tube mill model treats the range of bloom OD and WT values specified by the extrusion plant as constraints on the candidate bloom sizes. The tube mill management also redefined the model's objective function. Instead of minimizing the sum of annealing and tube drawing effort for all products, they wanted to assign higher priority to reducing the number of annealing operations since annealing and the associated material handling operations were perceived as the leading cause of defects. Thus, the revised model requires choosing a limited number of bloom sizes, within the range specified by the extrusion plant, in order to: (i) eliminate intermediate annealing steps for as many tubular products as possible, and (ii) secondarily, reduce the tube drawing effort (i.e., drawn-feet).

To quantify the minimum annealing requirement, a new metric called *k-coverage* was defined. k-coverage is the total volume (feet or pounds) of finished products that can be produced with k or fewer intermediate annealing operations using a given set of blooms. Thus, 0-coverage refers to the total volume of products that require no intermediate annealing operations. The MIT team developed and implemented a heuristic method that selects the required number of blooms to maximize k-coverage for any user-specified value of k (typically, 0, 1 or 2). By varying the required number of standard bloom sizes, the model can identify points on a tradeoff curve showing how % coverage increases with the number of standard blooms. This method was applied to the product mix derived from the tube mill database, but using new limits on bloom OD and WT specified by the extrusion plant. The new extrusion limits were quite stringent; in fact, several current blooms were outside the specified range. Nevertheless, the method chose 10 bloom sizes that together provided over 90% 1-coverage. Again, permitting new bloom sizes considerably increased coverage compared to restricting attention to current bloom sizes. These conclusions were reinforced when the model was applied to a new data set based upon information from more recent lot tickets.

Like the organizational changes in the second phase, the project environment changed during the third phase also. With the approaching deadlines for quantum leap improvements, supervisors concentrated on monitoring and expediting current orders in order to improve short-term performance, particularly on-time deliveries. Concurrently, ALCOA approved the tube mill's capital investment request to create one or two streamlined "cells" by rearranging pointers and draw-benches, and installing new materials handling equipment. Planning the acquisition and installation of equipment for this modernization project required considerable managerial attention. The plant proposed a

third LFM internship to study and improve the yield of the tube reducing operation, an optional intermediate stage between extrusion and tube drawing for products that require large CSA reduction from bloom. The LFM student performed various experiments to gauge the impact of reducer speed and bloom characteristics on process yield (Hofstetter [1993]).

During the third phase, funding arrangements for the project began to exert a stronger influence on its scope and direction. The MIT team had originally envisioned participation by both the extrusion plant and the tube mill; however, for accounting purposes, the limited funding needed for the project was "charged" to the tube mill's budget. Consequently, while the tube mill clearly considered itself to be a client for the project, the extrusion plant did not become fully involved in core team. This unequal participation was one of the factors that prompted the move to redefine the problem (from an integrated to a local model) for the second stage of implementation. The funding arrangements also impacted the level of participation by the ATC. Typically, the ATC relies on direct project-based funding from various plants to pursue relevant process development and engineering activities. When the plant originally approved the MIT project proposal, it agreed to provide research funding to MIT. However, the agreement did not explicitly cover funding for ATC to develop engineering process models for extrusion and tube drawing. In an environment with budget constraints and aggressive profitability improvement goals, the prospects of the plant allocating funds for long-term process understanding activities was less certain. So, the ATC's process modeling effort did not progress much beyond the initial explorations (during Phase 2). However, the ATC Division Manager continued to participate in the team's discussions and presentations at Lafayette both in his capacity as ALCOA's liaison to the LFM program and because he was personally committed and interested in the process engineering issues being addressed.

Recommendations, decision support tools, research:

Based on the solutions generated by the bloom sizing heuristics, the MIT team suggested a specific set of new bloom sizes that could more effectively cover the tube mill's product mix. At the time the project concluded, the extrusion plant had placed orders for the extrusion dies and associated tooling to produce some of these new bloom sizes. The Lafayette Works also decided to transfer to the tube mill the responsibility for planning and scheduling the main extrusion press that supplied most of the tube mill's extrusions. This press would remain under the operational jurisdiction of the extrusion plant; however, the tube mill would decide what bloom sizes to produce, as well as the lot sizes and timing for

each batch of blooms. Finally, the Extrusion/Tube System sponsored yet another LFM internship project at another tube manufacturing plant.

In addition to developing and testing bloom sizing algorithms, the MIT team also pursued the development of two user-friendly decision support tools–the *Tube Area Chart Viewer* (TACV) and a *spreadsheet* to perform what-if analyses–that the plant could use for short-term and medium-term planning. The TACV is a graphics tool, with pull-down menus and computing capabilities, to display an electronic Tube Area Chart showing the current set of standard bloom sizes, tube drawing constraints, and process plan for any chosen product. It runs on a personal computer (386 class machine) equipped with a mouse, co-processor, and VGA graphics. Building this tool first required translating the standard practice rules into mathematical inequalities expressed in terms of OD and WT. Each inequality represents one class of process constraints (e.g., maximum CSA reduction per draw). A process plan is feasible if its trajectory on the Tube Area Chart lies within the region defined by these constraints. Figure 4 shows a sample screen for the TACV program. This software can replace the current manual planning procedure, reducing the time to prepare the process plan for incoming orders, improving the accuracy of this plan, and facilitating sensitivity analyses. More importantly, the program presents a visual method to choose the "closest" available bloom for each order, enabling the plant to realize an estimated 20% savings in tube drawing effort. For a given set of process parameters, the TACV program also computes several metrics that characterize the process plan (e.g., number of draws, number of intermediate anneals, actual % CSA reduction per draw, and so on). Thus, the planner can change the available bloom set or the standard practice parameters, and observe, both visually and in terms of the performance metrics, how the chosen product's process plan changes. The TACV development effort went through several iterations; feedback from a planner at the tube mill led to refinements of the program to make it more user-friendly and robust.

In addition to the operational planning tool TACV, the MIT team also developed a spreadsheet program to support medium-term planning. The original implementations of the bloom size optimization heuristics (in FORTRAN and C) were meant to be used primarily for analysis and experimentation at MIT; they were not directly portable to the plant, nor did they permit easy human interaction during the optimization process. Since managers are accustomed to using spreadsheets, the MIT team decided to implement a PC-based version of the analysis tool using EXCEL. This program enables the user to manually select bloom sizes and study the overall performance impact of these choices

considering all of the tube mill's products. Another UROP student assisted in developing this software. The program takes as input the set of standard bloom sizes, parameters characterizing extrusion and tube drawing effort, standard practice parameters, and the product mix. It assigns each product to the closest bloom, and computes various performance metrics such as the number and total volume of products requiring 0, 1 or 2 anneals, the number of drawing passes needed for each product, the total extrusion and drawing effort, and so on. Users can add or delete blooms, and change the standard practice parameters. Using this program, planners could, for the first time, examine the tube mill's entire portfolio of products simultaneously to study the strategic impact of bloom sizing decisions.

The optimization problems dealing with the extrusion-tube drawing tradeoff motivated methodological research at MIT. The project led to a doctoral thesis in operations research (Gopalan [1992]) to address two generic optimization problems that apply to metal forming operations: (i) a new class of geometric location problems in the plane. Given, say, a rectangular area, the geometric location model requires selecting a minimum number of points, each of which can cover a limited region to the left and below that point, such that the entire rectangle is covered. For the bloom sizing problem, the rectangle corresponds to the region on the Tube Area Chart containing all the tubular products, and each chosen point represents a standard bloom size; and (ii) a new inventory planning model incorporating both commonality (i.e., using the same bloom size to produce multiple products) and flexibility (i.e., ability to use an alternate bloom when the preferred bloom size for a product is not available in inventory). The model selects standard bloom sizes and determines the optimal inventory policy, considering both the cost of converting blooms to finished products as well as the savings in safety stocks due to commonality. The project also motivated an undergraduate thesis (DelCallar [1992]) to study the effectiveness of genetic algorithms to select optimal bloom sizes. Currently, another OR Center graduate student is addressing optimization and inventory management issues associated with selecting standard lengths for each bloom. Finally, the project also provided a case study for a course on "Operations Management Models and Applications" at the Sloan School.

4. Project Impacts and Lessons

The project provided many benefits both to ALCOA and the MIT researchers and students. Section 3 listed some of the "products" including new metrics and models for process planning, two personal computer-based tools–the TACV and the planning

spreadsheet–to support operational and tactical process planning decisions, statistical methods and optimization heuristics for bloom sizing, and specific recommendations regarding new bloom sizes. The plant ordered new extrusion dies to produce the recommended sizes, and integrated the planning function for the extrusion press and tube mill. In addition to these tangible outcomes, the project had a much broader impact both in terms of a better understanding of the process planning choices in metal-forming operations, and lessons for improving collaborative industry-university projects. We discuss some of these broader project impacts and present a retrospective view of the project.

Considering the wide diversity of the project team and the numerous organizational changes during the two years, the project was remarkably successful in meeting several initial goals. The project brought together Alcoans from the plant, the division, and the corporate research center with MIT faculty and students from the Schools of Engineering and Management. Participants from the plant ranged from shop-floor supervisors and planners to plant and division managers. MIT and ALCOA personnel interacted quite frequently. During the course of the project, MIT faculty visited the plant at least 10 times, and ALCOA personnel (the tube mill plant manager, planning supervisor, process planner, and ATC Division manager) visited MIT several times. In addition, 3 LFM interns spent 6 months each at the plant. The project provided an opportunity for undergraduate, masters', and doctoral students in engineering, management, and operations research to gain exposure and contribute to practice. It led to three LFM theses, one undergraduate thesis in computer science, a doctoral thesis in operations research, plus new teaching material and some ongoing research.

Although the plant did not participate as actively as orginally anticipated, the project played an important role, via the periodic communications and presentations at the plant, as an ongoing consciousness-raising mechanism to address long-term issues in an environment characerized by severe short-term pressures. It sensitized management to three main themes: (i) process planning has strategic importance for "process" industries such as tube manufacturing that have a wide range of process flexibility but also close interdependence between successive stages in the manufacturing chain; (ii) exploiting this flexibility requires a systems view, i.e., medium and long-term process planning decisions must jointly consider the impact on multiple stages in the chain and examine the entire portfolio of products. This approach contrasts with the traditional emphasis on the daily, operational planning activity that treats each stage and product in isolation; and, (iii)

planning and process engineering activities are closely tied, with process parameters serving as input to the planning model, while sensitivity analyses of plans help to prioritize process improvement efforts. These observations were not necessarily new to the plant managers and supervisors, many of whom had over 20 years experience with tube manufacturing. However, the data analyses, planning models, and tools from the project provided a means to confirm this intuition and quantify the potential improvements.

The organizational change during the third phase, when the Lafayette Works transferred the responsibility for planning both extrusion and tube mill operations to a single production planning group, suggests that the project was successful in conveying the importance of integrated multi-stage planning. Another indicator of the project's positive impact is the plant's decision to hire an LFM graduate full-time, and sponsor several LFM internships. The LFM curriculum emphasizes the importance of simultaneously addressing both the technical and managerial aspects of manufacturing problems, and is tailored to provide the requisite engineering and management skills. The Lafayette management's enthusiasm to involve LFM students reflects in part their favorable experience working with MIT faculty and students, and the recognition that, to attain world-class status in the industry, the plant must bridge the engineering-planning gap.

The team's attempts to develop formal diagnostic tools and mathematical models had two side benefits: (i) it served to highlight the need to develop good non-financial metrics to measure productivity and output in the tube mill and extrusion plant. Several new metrics such as drawn-feet, total rack area, and effective extrusion speed were defined, and the analysis illustrated how the choice of metrics can influence the process planning decisions: and, (ii) it pointed to deficiencies in existing information systems. The project also provided intangible benefits to MIT researchers. It generated insights on how to characterize flexibility in metal-forming processes, created opportunities to understand the extrusion and tube drawing processes, and provided a specific context to test hypotheses and process planning methodologies that can have broader applications. As an experiment in multi-disciplinary, industry-university partnership, the learning experience from the project was itself an important benefit to both MIT and ALCOA. We next discuss some of these lessons and identify opportunities to improve the effectiveness of future collaborations.

What were the critical factors that led to the successful project outcomes? Clearly, important prerequisites include personal chemistry of the team participants, and their

common belief that research and practice can be synergistic in improving manufacturing while also extending the state of knowledge. The LFM program was a key enabler for the project. The program provides faculty ready access to the partner companies' manufacturing operations, and at the same time links company representatives to appropriate faculty; it also provides cross-trained students who are committed to manufacturing. The sponsorship and joint supervision needs of LFM internships creates opportunities for interdisciplinary and industry-university collaboration. The program also provides funding for graduate students (in addition to LFM students) and travel to pursue manufacturing research at partner companies. Because these projects do not rely exclusively on corporate funding, faculty can address long-term issues and might feel less constrained in critically evaluating current practice or suggesting radical changes.

The 6-month, on-site LFM internship is both a good learning experience for students and also increases communication between university and industry. The students help the faculty to quickly understand the current operations and also serve as interpreters between faculty and plant management. We might note that, because of these numerous support mechanisms, the LFM program has fostered several other collaborative projects with partner companies on topics ranging from rapid prototyping to product and process development and scheduling. The LFM partner companies participate actively in setting the program's policies and priorities, and one of these priorities is to promote industry-university collaboration. Since the proposed project was consistent with this mission, senior managers at ALCOA viewed it favorably and encouraged plant participation. Another factor that facilitated the project was the flexible academic arrangements at MIT. Programs such as UROP and the OR Center permit interested students to participate in multi-disciplinary projects, enabling us to bring together students with different skills to address various facets of the problem.

The project experience also provided lessons on the potential bottlenecks and obstacles that can reduce the effectiveness of collaborative projects. Some of these lessons are generic, i.e., they apply broadly to industry-university collaboration, while others pertain to the specific type of project that we undertook, namely, supply chain integration. We first discuss pitfalls in collaborative projects, before addressing the challenges in supply chain integration.

Lessons for collaborative projects:

Chief among the pitfalls of industry-university and interdisciplinary collaborative projects are:

- the conflicting goals of various stakeholders,
- organizational transitions and changing priorities during and after the project,
- differences in expectations and project time frames,
- inadequate organizational learning mechanisms, and
- inadequate team expertise in issues relating to organizational redesign and change.

Both engineering and management science have a rich heritage of successful industry-university collaboration because both fields are problem-driven. We suspect that this collaboration often stems from personal contacts and possibly consulting arrangements. Our project was somewhat unique because it was explicitly designed as a "research" rather than a consulting arrangement, and the participants (including the two faculty members) had not previously collaborated. This type of project evolution and arrangement not only increases the level of uncertainty regarding the project outcomes and benefits, but also sharpens the contrast between the goals of the participating managers and university researchers.

Typically, academics hope that collaboration will provide one or more of the following benefits: (i) the project motivates a problem that they can then subsequently address in their research; (ii) they have access to real data that they can use to test their theories and methodologies; (iii) the practitioners can critique and endorse their models, thus improving the credibility of the research; (iv) the models and methods are actually implemented, providing case studies that document tangible evidence of the research's technical or economic value; (v) the project provides unusual opportunities to learn, and access to a particular technology, topic, or industry that can later serve as the researcher's distinctive competence; (vi) the project enhances the educational program by creating opportunities for students to observe and apply their knowledge to practice, motivating case studies for class discussion, and providing access to jobs. Other academic motives might include establishing a long-term relationship with a particular company or plant to build and sustain a coherent research program. In return, academics bring their specialized skills, analytical and conceptual capabilities, benchmarking expertise, and knowledge about the state-of-the-art in particular disciplines. They are not necessarily well-equipped to contribute to actual implementation, particularly if the project requires production quality software that must be integrated with the organization's existing information systems. One common metric that academics use for evaluating the success of a project is the number (and quality) of research

publications and student theses resulting from the project. Other metrics might include curriculum innovations, and the number of students supported by the project.

Contrast these academic goals with the objectives of a plant manager whose main prior external interaction might have been with consultants. Plant managers are more likely to support applied rather than fundamental research; moreover, they are mainly interested in projects that address current priorities in their particular operations. They look to academics to generate new ideas or transfer state-of-the-art technology to the organization and perhaps act as change agents. Fundamental, long-term research is often the domain of corporate research centers. Plant managers are more oriented towards negotiating specific time-bound deliverables and monitoring progress against these commitments. They are accustomed to receiving specific recommendations rather than general principles and methods that their organization must assimilate and implement. Return on investment is a common metric to evaluate the success of a project.

These differing goals of researchers and practitioners can create tensions that impede project progress. Managers need periodic reminders about the distinction between research and consulting projects, while academics need incentives to align their research with practice. The academics must try to convince professional colleagues that the work has intellectual merit, while managers attempt to justify projects in the context of their current performance goals. Differences in time frames and expectations further complicate this interaction. Managers are more likely to turn to external change agents during "difficult" times, but research might not proceed at the required pace. As we have seen, the company's accounting arrangements to fund the project can also influence the project's direction. On the one hand, funding from a corporate research account (rather than a plant's budget) can reduce the pressure to provide demonstrable short-term benefits in terms of plant profitability and productivity. However, this arrangement has the potential hazard of reducing the plant's involvement in the project. On the academic side, researchers must be flexible enough to accommodate changes in the project scope including redefinition of the problem. Otherwise, they face the risk of obsolete and irrelevant research particularly as organizations become more adept at changing the way they operate to respond effectively to the dynamic marketplace.

We should add that the tensions that develop, if recognized and discussed openly, can also work constructively for the collaboration process. Academic researchers benefit from an insistence on relevant research with an eye to continued progress, while plant managers

benefit from a collaboration that forces them to consider a longer time horizon for development work. The press of daily or weekly requirements may encourage inappropriate decisions because the time is not available to collect appropriate data and analyze them. Collaboration with academic researchers may encourage a longer term outlook when other portions of the organization are forcing short term solutions. Ideally, the collaboration continues such that differences, if they exist, are reduced when they should and appreciated and exploited when they should not. In other words, "vive la difference."

When the project is interdisciplinary, differences in the incentives and priorities for researchers from different fields introduces an additional level of complexity. For instance, management scientists have available a variety of publication outlets ranging from theoretical to algorithmic and application-oriented journals. Consequently, an operations improvement project poses less risk that the project will not lead to publications. On the other hand, engineering research at universities focusses more on understanding, experimenting with, or improving leading edge technology. A project that requires applying traditional techniques such as finite-element simulation to a mature technology might not offer attractive research potential. Furthermore, management schools might be more accustomed to interdisciplinary research, whereas academic recognition in an engineering research discipline might require a greater degree of specialization. Finally, practitioners often appear to believe that their organizations are well-equipped to handle and solve technical problems, and that "managerial" problems are the root cause of poor performance. A project that attempts to integrate engineering and management must first overcome this stereotype.

Frequent realignment and organizational restructuring is another impediment to multi-year projects. Ideally, industry-university collaboration should be a team effort with active participation by both practitioners and researchers. This mode is particularly advantageous to transfer technology from universities to industry; plant representatives on the team learn the technology and are responsible for implementing it. Organizational transitions and the consequent shifting priorities makes sustained team effort difficult. We know of several promising projects that did not reach successful implementation because the original project champion moved to a different position in the organization or a more pressing problem emerged. Projects can also fail because the skills represented in the team are not adequate. For instance, operations improvement projects require introducing change, and so can benefit from participation in the team by experts in change management. Other important

pitfalls include lack of top management support to allocate time and resources to the team, and difficulties in data collection.

Lessons for supply chain integration:

The initial project proposal was very ambitious. The project scope implicitly included (i) collecting data and performing diagnostic analysis to validate the hypothesis regarding the importance of integrated medium-term process planning decisions, (ii) convincing management about the importance of the project, (iii) developing and testing process and decision support models to facilitate integrated process planning, and (iv) implementing (at least partially) these concepts. The long-term vision was to promote tighter integration of the supply chain from ingot casting to finishing and shipping. To keep the project tractable, it focussed on integrating two intermediate stages–extrusion and tube drawing–of the longer chain.

The team accomplished many of the initial objectives, including a virtual integration of extrusion and tube-drawing through a merger of planning functions. Nevertheless, the experience highlighted some of the special needs of supply chain integration projects whose importance the team members did not fully appreciate at the outset. In particular, integrating the different stakeholders in the chain requires progress on many different fronts: organizational restructuring, cultural change, realignment of incentives and performance evaluation criteria, and appropriate information and decision support systems. The project emphasized the systems aspect since the two faculty members were best equipped to contribute to this area. Perhaps, including in the team other researchers interested in organizational development and change might have been beneficial. But more importantly, supply chain integration requires greater involvement from the plant compared to other collaborative projects dealing with well-defined process engineering or decision modeling issues.

Consider a traditional "functional" organization that treats each stage of the supply chain as a separate entity with its own manager. Every manager is responsible for "local" performance of his/her organization, typically measured in terms of cost, quality, productivity, inventory, and so on. Often, these productivity-based local performance metrics are not necessarily consistent with overall plant performance, i.e., "optimizing" local performance might produce suboptimal decisions for the plant as a whole. In the tube manufacturing context, for example, measuring extrusion performance solely in terms of press productivity (total pounds extruded per hour) leads the extrusion plant to strongly

prefer producing large diameter, thick wall blooms. However, this strategy increases the workload and decreases the yield in the tube mill. Furthermore, towards the end of each performance evaluation interval (e.g., month or quarter), the extrusion plant might expedite production of larger blooms in order to meet its performance goals even though these batches have lower priority in terms of meeting customer due dates. In this setting, as customer demand shifts towards thin wall tubes, costs and lead times increase making the facility less competitive. Supply chain integration can break this pattern by making the extrusion and tube drawing plants jointly responsible for overall performance. However, institutionalizing this mode of operation requires a fundamental change in the organizational culture from an individualistic to a team orientation at all levels of the hierarchy.

This cultural change must be accompanied by changes in the organization structure as well as performance evaluation and incentive systems to make them consistent with the shared responsibilities. The extrusion press, draw benches, and annealing ovens are "prime" equipment, and so the managers might continue monitoring (and holding their supervisors responsible for) utilization, yield, and productivity of individual work centers. However, at higher managerial levels, the extrusion and tube managers should be held jointly accountable for total (extrusion + drawing) cost, total inventory (of blooms + WIP and finished tubes), overall ingot-to-finished tube yield, and delivery performance to the end customer (versus performance with respect to artificial due dates for extrusion). This type of arrangement would necessitate frequent dialog and process planning negotiations between the extrusion and tube plants, providing the appropriate environment for our analysis and decision tools. The initial project scope did not include a study of issues relating to cultural change, organization restructuring or incentives. Instead, the project implicitly assumed that these changes would be in place by the time the organization was ready to implement the decision support models that were developed. Clear recognition of this implicit assumption at the outset would have made the project more effective.

5. Conclusions

The ALCOA-MIT project at Lafayette was an experiment in cross disciplinary, industry-university collaboration. This type of collaboration for mutual benefit is likely to increase, particularly in the manufacturing domain, due to the increasing uncertainties associated with government funding for university research projects and the recognition that academia must help industry, through its educational programs and research, in achieving manufacturing excellence. By emphasizing the process of collaboration, we hope this paper can serve as a source of ideas regarding opportunities and mechanisms to

improve the effectiveness of future collaborations. To be sure, the project had several unique elements such as the initial circumstances that led to the collaboration. Nevertheless, it has also provided several important lessons that apply more broadly. In particular, this experience suggests the following minimal ingredients for a successful industry-university research effort.

1. There should be sufficient personal familiarity to permit open exchange of ideas. Substantial up front time may be necessary to lay the foundation for collaboration.

2. The expectations and needs of the different participants should be discussed both at the beginning and throughout the duration of the project.

3. Some mechanisms must be established to ensure participation by all involved. These can include allocation of specific tasks, regular meetings (faithfully attended), exchange of personnel, and small teams cutting across organizational boundaries. Contribution of funding alone is not a sufficient guarantee of participation; the participating organizations must make explicit commitments to assign personnel to the project.

4. Flexibility is essential. Priorities change, not only because of changing economic pressures, but because a project may identify important, previously unappreciated issues.

5. Thought should be given to appropriate team content. Most projects are highly interdisciplinary and university research sometimes does not operate well in these circumstances.

Our historical perspective has also highlighted the critical importance of a visible umbrella program such as LFM, governed jointly by industry and university, to help overcome stereotypes, establish the importance of longer term perspectives (or at least help balance short and long-term perspectives), and provide access to people, information and resources (e.g., travel funds). We believe that multi-functional, industry-university teams provide an effective means to address in depth medium and long-term problems facing industry, while also motivating academic research. However, making these teams work entails considerable overhead for coordination, and requires an appreciation and alignment of individual goals. The process is not free of pitfalls and a careful attention to the process as well as the product is important.

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Figure 1: Schematic of Tube Manufacturing Process

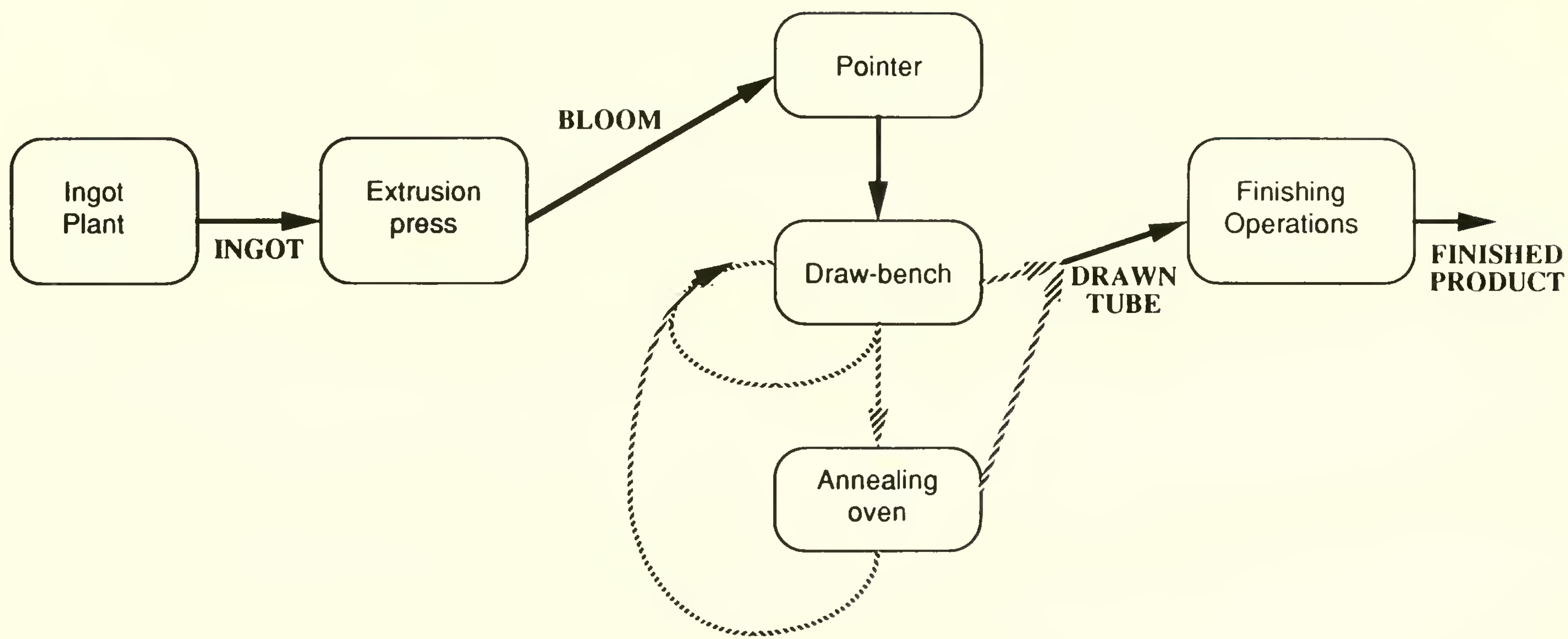

Figure 2: Process plan representation on Tube Area Chart

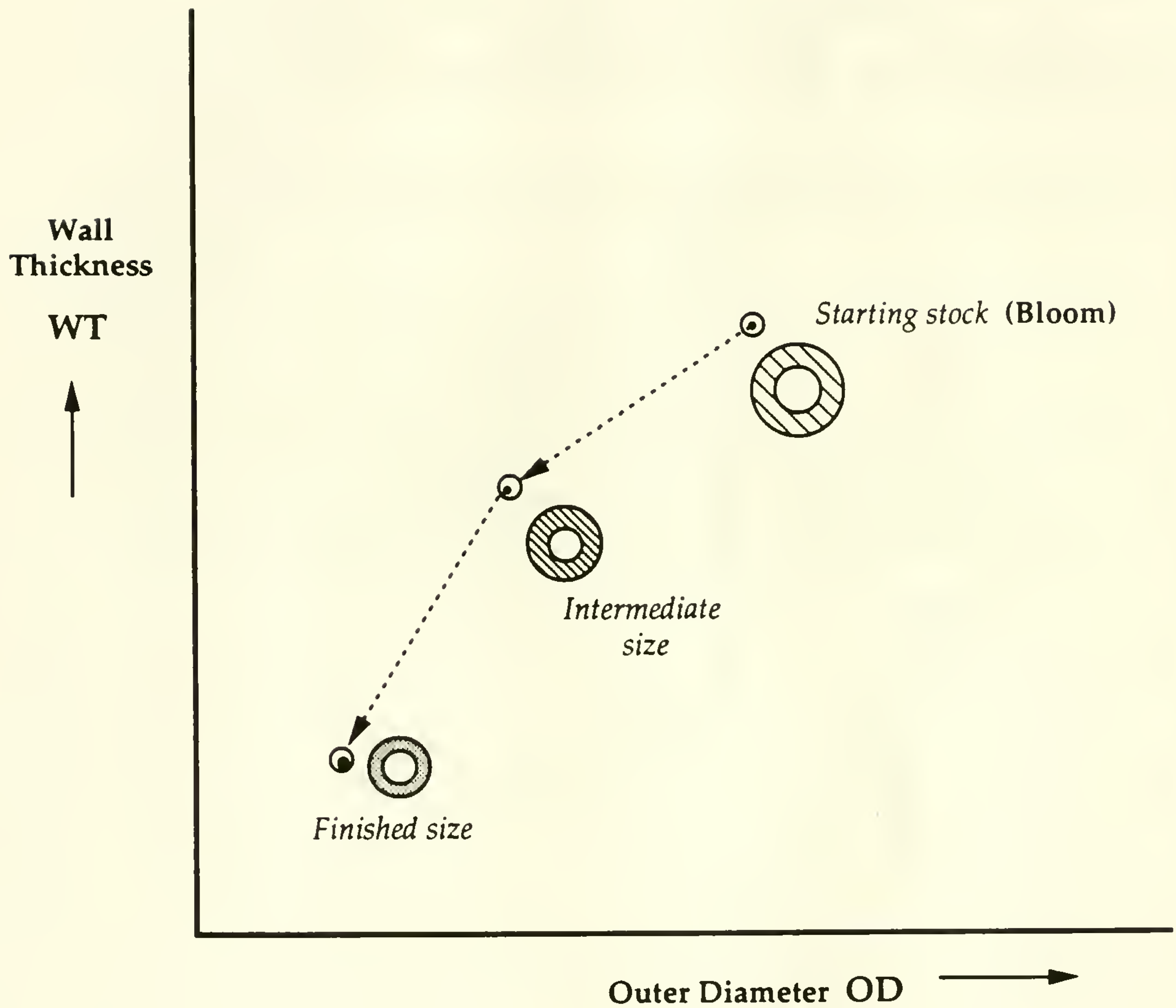

Figure 3: Tradeoff Curves and Sensitivity Analysis of Extrusion versus Tube Drawing Effort

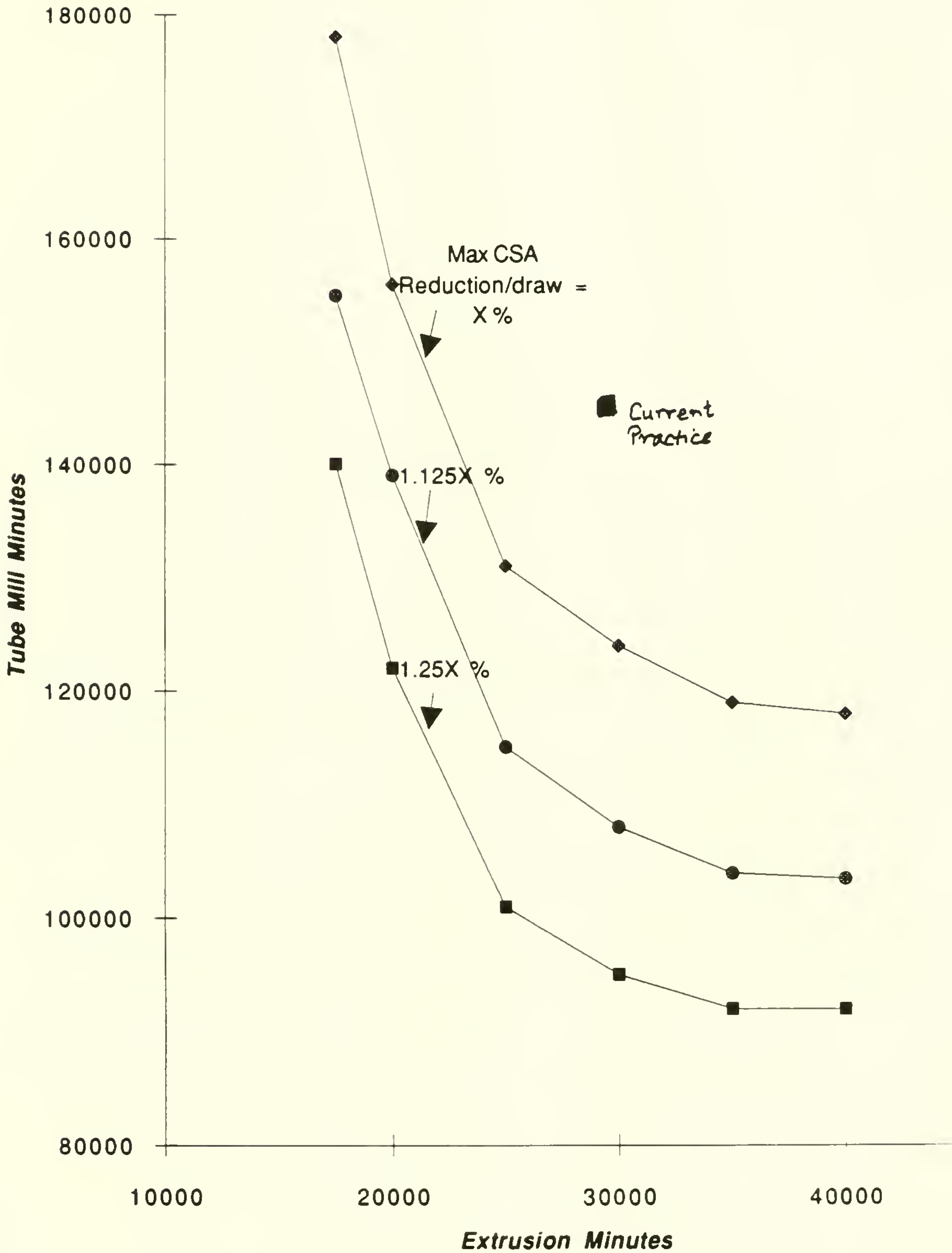

Figure 4: Sample screen for Tube Area Chart Viewer program